

Observational Constraints on Kinetic Gravity Braiding from the Integrated Sachs-Wolfe Effect

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The cross-correlation between the integrated Sachs-Wolfe (ISW) effect and the large scale structure (LSS) is a powerful tool to constrain dark energy and alternative theories of gravity. In this paper, we obtain observational constraints on kinetic gravity braiding from the ISW-LSS cross-correlation. We find that the late-time ISW effect in the kinetic gravity braiding model anti-correlates with large scale structures in a wide range of parameters, which clearly demonstrates how one can distinguish modified gravity theories from the Λ CDM model using the ISW effect. In addition to the analysis based on a concrete model, we investigate a future prospect of the ISW-LSS cross-correlation by using a phenomenological parametrization of modified gravity models.

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I. INTRODUCTION

Modifying general relativity at long distances is a possible way to explain the present accelerated expansion of the Universe indicated by different cosmological observations such as type Ia supernovae [1, 2], the cosmic microwave background (CMB) anisotropies [3, 4], the large scale structure (LSS) of galaxies [5, 6], and clusters of galaxies [7, 8]. A number of modified gravity models have been proposed so far, including scalar-tensor theories, $f(R)$ gravity [9–15], the Dvali-Gabadadze-Porrati (DGP) brane model [16, 17], and galileon gravity [18].

Recently, the galileon gravity model has attracted considerable attention, which is constructed by introducing the scalar field with the self-interaction whose Lagrangian is invariant in the Minkowski space-time under the Galilean symmetry $\partial_\mu\phi \rightarrow \partial_\mu\phi + b_\mu$, which keeps equation of motion the second order differential equation with no ghostlike instabilities [18]. A remarkable property of the galileon model is the Vainshtein mechanism that the self-interaction terms induce the decoupling of the galileon field ϕ from gravity at small scale [19]. This allows the galileon theory to recover general relativity around a high density region, which ensures the consistency with the solar system experiments. Furthermore, the galileon model can lead to the late-time accelerated expansion of the universe, which can be useful as an alternative to the simple dark energy model.

Cosmology of the galileon model has been extensively investigated by many authors [20–38]. Recently, Deffayet *et al.* [39] proposed the most generalized scalar-tensor theory, including $f(R)$ theories, galileon theories and the kinetic gravity braiding [40–42]. In addition, several authors have investigated the observational constraints on various galileon theories from type Ia supernovae, the CMB shift parameter, baryon acoustic oscillations and the growth rate of matter density perturbations [43–46].

It was pointed out that the integrated Sachs-Wolfe effect can distinguish between the galileon model and the

Λ CDM model, which was discussed in the scalar-tensor galileon model [24]. In contrast to the Λ CDM model, in which the gravitational potentials decay because of the accelerated expansion of the universe, the amplitude of the gravitational potentials in the galileon model may increase due to perturbations of the galileon field. In these two models, the integrated Sachs-Wolfe effect predicts opposite signs. Therefore, this provides us with a useful chance to test the galileon model using a cross-correlation between the matter (galaxy) distribution and the cosmic microwave background anisotropies [47, 48]. In the present paper, we focus our investigation on the observational constraints from the cross-correlation between the CMB anisotropies and the galaxy distributions.

Throughout the paper, we use units in which the speed of light and the Planck constant are unity, $c = \hbar = 1$, and M_{Pl} is the reduced Planck mass related with Newton's gravitational constant by $M_{\text{Pl}} = 1/\sqrt{8\pi G}$. We follow the metric signature convention $(-, +, +, +)$.

II. KINETIC GRAVITY BRAIDING MODEL

We start with the most general minimally coupled scalar field theory with second-order field equations [31, 40], whose action is of the form

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R + K(\phi, X) - G(\phi, X) \square\phi + \mathcal{L}_m \right], \quad (1)$$

where R is the Ricci scalar, $K(\phi, X)$ and $G(\phi, X)$ are arbitrary functions of the scalar field ϕ and its kinetic term $X := -g^{\mu\nu} \nabla_\mu\phi \nabla_\nu\phi/2$, $\square\phi = g^{\mu\nu} \nabla_\mu \nabla_\nu \phi$, and \mathcal{L}_m is the matter Lagrangian. Although ϕ is not directly coupled to R , the interaction $G\square\phi$ causes “braiding” of the scalar field and the metric, giving rise to non-trivial and interesting cosmology. In this paper, we consider the shift symmetric case, $K = K(X)$ and $G = G(X)$, for which an attractor solution is generically present [34, 40], leading to a late-time de Sitter expansion driven by

constant kinetic energy of ϕ . In particular, we focus on the following model [42]:

$$K(X) = -X, \quad (2)$$

$$G(X) = M_{\text{Pl}} \left(\frac{r_c^2}{M_{\text{Pl}}^2} X \right)^n, \quad (3)$$

where n and r_c are the model parameters, though r_c is required to be tuned as $r_c \sim H_0^{-1}$. Throughout the paper we consider for simplicity the cosmological evolution along the attractor, assuming that the background solution converges to the attractor at some sufficiently early time.

We work in the spatially flat Friedmann-Robertson-Walker Universe and consider the metric perturbations in the conformal Newtonian gauge,

$$ds^2 = a^2(\eta) \left[-(1 + 2\Psi)d\eta^2 + (1 + 2\Phi)(d\chi^2 + \chi^2 d\Omega_{(2)}^2) \right], \quad (4)$$

where the scale factor a is normalized to unity at the present epoch, η is the conformal time, χ is the co-moving distance and $d\Omega_{(2)}^2$ is the line element on a unit sphere. The quasi-static approximation is applicable for $\mathcal{O}(k^2 c_s^2/a^2) \gg \mathcal{O}(H^2)$, which corresponds to $n \lesssim 10$ for the wavenumber $k \gtrsim 0.01 h\text{Mpc}^{-1}$. Under this approximation, the modified Poisson equation may be written as

$$\nabla^2 \Psi \simeq 4\pi G_{\text{eff}} a^2 \rho_m \delta, \quad (5)$$

where ρ_m is the energy density of matter, δ is the matter density contrast, and G_{eff} is the effective gravitational coupling,

$$G_{\text{eff}} = G \frac{2n + 3n\Omega_m(a) - \Omega_m(a)}{\Omega_m(a)[5n - \Omega_m(a)]}. \quad (6)$$

The traceless part of the Einstein equations is given by

$$\Psi + \Phi = 0. \quad (7)$$

The evolution equation for the matter overdensity δ is given by

$$\ddot{\delta} + 2H\dot{\delta} \simeq \frac{\nabla^2}{a^2} \Psi. \quad (8)$$

For large n , the quasi-static approximation no longer works. In this case, one needs to solve the full perturbation equations. The full perturbation equations and the validity of the quasi-static approximation are investigated in [42]. For convenience, we define $U_k(\eta)$ as

$$-k^2 \frac{\Psi_{\mathbf{k}} - \Phi_{\mathbf{k}}}{2} = \frac{3}{2} \Omega_0 H_0^2 U_k(\eta) \delta_{\mathbf{k}}(\eta_0), \quad (9)$$

where $\Psi_{\mathbf{k}}$, $\Phi_{\mathbf{k}}$ and $\delta_{\mathbf{k}}$ are the metric perturbations and the energy density contrast in Fourier space, respectively. As long as the quasi-static approximation holds, $U_k(\eta) = (G_{\text{eff}}/G)(D_1(\eta)/aD_1(\eta_0))$, where $D_1(\eta)$ is the

growth factor of the kinetic gravity braiding model normalized as $D_1(\eta) = a$ at early stage of the evolution and η_0 is the present conformal time.

The authors of Ref. [42] obtained the observational constraints on the kinetic gravity braiding model with the functions (2) and (3) from type Ia supernovae, the WMAP CMB anisotropy experiment, and the Sloan Digital Sky Survey (SDSS) luminous red galaxy (LRG) samples. The result of Ref. [42] indicates that models with larger n better fit the CMB distance observation, though the constraints derived there are not so strong. In this paper, we will improve the constraints significantly by using the galaxy-CMB cross-correlation.

III. ISW-GALAXY CROSS-CORRELATION

The ISW effect contributes to the power spectrum of the CMB anisotropy on large scales. However, the direct detection of the ISW effect is very difficult due to the cosmic variance and the relatively small amplitude of the ISW effect in the power spectrum. Nevertheless, by cross-correlating the CMB anisotropies and the galaxy number density fluctuations, one can isolate the ISW effect, which will be a powerful probe of dark energy and modified gravity models. The ISW effect in the CMB anisotropy is given by

$$\frac{\Delta T(\vec{\gamma})}{T} = \int_{\eta_d}^{\eta_0} d\eta [\Psi'(\eta, \mathbf{x}) - \Phi'(\eta, \mathbf{x})], \quad (10)$$

where η_d is the decoupling time, which may be taken to be zero practically, and the prime denotes the differentiation with respect to η . The fluctuations in the angular distribution of galaxies is given by

$$\frac{\Delta N_g(\vec{\gamma})}{N} = \int_0^{z_d} dz \delta_g(\eta, \mathbf{x}) \mathcal{W}(z), \quad (11)$$

where $\mathcal{W}(\chi)$ is the selection function and δ_g is the galaxy number density contrast, which is related to the energy density contrast δ through the bias b as $\delta_g = b(k, z)\delta$. The cross-correlation of the galaxy fluctuations and the CMB anisotropies is thus expressed as

$$\left\langle \frac{\Delta T(\vec{\gamma})}{T} \frac{\Delta N_g(\vec{\gamma}')}{N} \right\rangle = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_{\ell} \mathcal{P}_{\ell}(\mu), \quad (12)$$

where \mathcal{P}_{ℓ} is the Legendre polynomial with μ being the cosine of the angle between $\vec{\gamma}$ and $\vec{\gamma}'$,

$$C_{\ell} = \frac{3\Omega_0 H_0^2}{(\ell + 1/2)^2} \int dz H(z) \mathcal{W}(z) \frac{D_1(z)}{D_1(z=0)} \times \left. \frac{dU_k(\eta)}{dz} b(z, k) P(k) \right|_{k=(\ell+1/2)/\chi}, \quad (13)$$

and $P(k)$ is the matter power spectrum at the present time, $\eta = \eta_0$. In deriving the above equation, we used the small angle approximation, $l \gg 1$.

IV. COMPARISON WITH OBSERVATIONS

Figure 1 shows the measured cross-correlation function for the six catalogues (2MASS, SDSS galaxies, LRG, NVSS, HEAO, and QSO) available in Ref. [53].¹ The solid and dashed curves show the theoretical predictions for the Λ CDM model and the kinetic braiding model with $n = 1, 10, 100, 1000$, and 5000 . We fixed the baryon density as $\Omega_b = 0.0451$, the matter density as $\Omega_0 h^2 = 0.1338$, the hubble constant as $h = 0.702$, the spectral index as $n_s = 0.966$, and the amplitude of the density fluctuation as $\Delta_{\mathcal{R}}^2 = 2.42 \times 10^{-9}$ at $k_0 = 0.002 \text{ Mpc}^{-1}$ [4]. The galaxy bias of each catalog is found in Ref. [53] and the values are $b = 1.4, 1.0, 1.8, 1.5, 1.06$ and 2.3 for 2MASS, SDSS galaxies, SDSS LRG, NVSS, HEAO, and QSO, respectively. For the theoretical modeling of the power spectrum, we used the linear power spectrum with the transfer function $T(k)$ of Eisenstein and Hu [76] and obtained Ψ , Φ , and δ by solving the full perturbation equations. As we can see from Fig. 1, the cross-correlation function for the kinetic gravity braiding model with larger n is closer to that for the Λ CDM model, and they are practically indistinguishable for $n > \mathcal{O}(1000)$. This is because the perturbation of the kinetic term δX become zero in the limit of $n \rightarrow \infty$ [42]. Another important feature found in Fig. 1 is the anti-correlation for the kinetic gravity braiding model with small n . This is caused by the enhancement of the effective gravitational coupling G_{eff} and the consequent growth of the gravitational potential, leading to the opposite sign of the function $dU_k(z)/dz$ compared to the Λ CDM model. Since the measurements of the cross-correlation function in each catalog shows a positive correlation, kinetic gravity braiding with small n will be inconsistent with observations.

In our analysis, the total chi squared is given by

$$\chi_{\text{total}}^2 = \sum_{i,j} (c_i^{\text{obs}} - c_i^{\text{theo}}) C_{ij}^{-1} (c_j^{\text{obs}} - c_j^{\text{theo}}), \quad (14)$$

where c_i^{obs} is the cross-correlation function obtained from observations, c_i^{theo} is the cross-correlation function theoretically predicted from Eq. (12), and C_{ij}^{-1} is the inverse of the covariance matrix obtained from [53]. For the WMAP cosmological parameters [4], we obtained the lower bound

$$n > 4.2 \times 10^3 \quad (95\% \text{ C.L.}). \quad (15)$$

As we expected from Fig. 1, the kinetic gravity braiding model with small n is obviously ruled out, while the

model with large n is favored by observations. This is because the ISW effect anti-correlates with the LSS for $n < \mathcal{O}(1000)$, and the sign of the cross-correlation function determines the lower bound (15). Note that the galaxy bias in Ref. [53] is obtained from the two-point correlation functions of each catalog assuming the Λ CDM model. In our case, the matter power spectrum for $n \gtrsim 1000$ and $0.001 \text{ hMpc}^{-1} \lesssim k \lesssim 0.1 \text{ hMpc}^{-1}$, which is the dominant wavenumber in Eq. (13), is almost the same as those in the Λ CDM model. Therefore, this is not problematic, and we also confirmed that using the galaxy bias of the Λ CDM model does not significantly change the results of chi-squared analysis. The lower bound (15) changes within only 10 percent even when we assume the bias as free parameters. This is because the constraint on the model parameter n is determined by the sign of the cross-correlation function, which is almost independent of nature of bias.

V. PARAMETRIZED MODEL

In the previous section, we have demonstrated that the ISW-galaxy cross-correlation strongly constrains kinetic gravity braiding. The key to this result was the *time-evolution* of the gravitational potential controlled by the effective gravitational coupling G_{eff} in the density perturbation equation. In this section, we employ a phenomenological parametrization of the *time-evolution* of G_{eff} rather than G_{eff} derived from a concrete model, and investigate how the parameters are constrained by tomographic observations. This approach is useful to estimate a general prospect of constraints on generalized models (e.g., [36]).

Provided that the quasi-static approximation is valid, the evolution of overdensities is described by the equation of the form (8) with (5) in *all* the scalar-tensor theories with second-order field equations [36] including kinetic gravity braiding. We parametrize the evolution of G_{eff} as follows:

$$\frac{G_{\text{eff}}}{G} = 1 + g_1 a^{g_2}, \quad (16)$$

where g_1 and g_2 are the free parameters. This reproduces the effective gravitational coupling e.g., of the kinetic gravity braiding model considered in this paper for small n . In particular, the effective gravitational coupling with $g_1 = 1$ and $g_2 = 4$ yields that of the kinetic gravity braiding model for $n = 1$ within a few percent precision. We consider the model whose sound speed for the scalar field does not approach zero. This means the quasi-static approximation is applicable for the dominant wavenumbers in Eq. (13). Then, the evolution equation for the matter overdensity and the Poisson equation are of the form Eqs. (8) and (9). In the case of a minimally coupled scalar field model, the traceless part of the Einstein equations gives $\Psi + \Phi = 0$.

In this section, we present the observational constraints on the above parametrized model and perform the Fisher

¹ Most ISW detections have less than 3σ detection level [49–73]. In addition, the authors in Ref. [75] claimed the possibility of the absence of ISW signal extracted from the five-year WMAP data and the AAOmega LRG redshift survey. Although the detection of the cross-correlation between the cosmic microwave background and the large scale structure has been under debate (see, e.g., [74]), we use the result of a combined analysis of the six catalogues in Ref. [53], which is the highest detection ($\sim 4.5\sigma$).

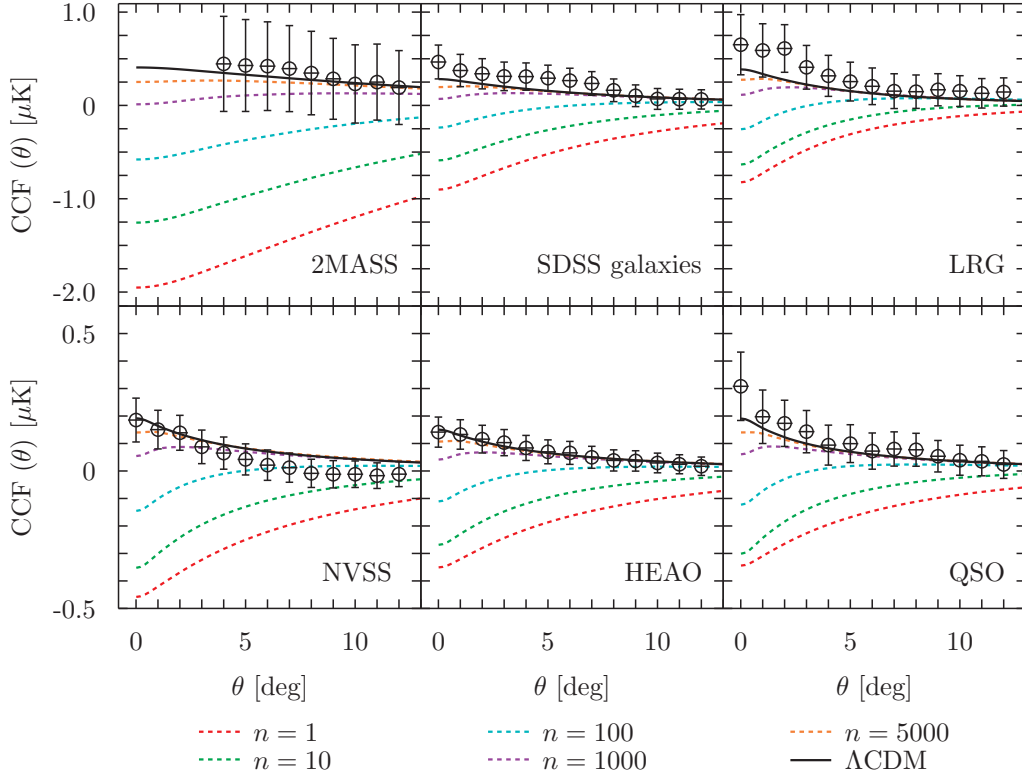


FIG. 1: The cross-correlation function theoretically calculated by using Eq. (12) and the data obtained in [53]. Each curve shows the cross-correlation function of the Λ CDM model (solid curve), the KGB model (dashed curve) with $n = 5000, 1000, 100, 10$, and 1 , from the top to the bottom, respectively.

matrix analysis. Figure 2 shows the contour of $\Delta\chi^2$ on the $g_1 - g_2$ plane. We assumed that the background expansion history is the same as that of the standard Λ CDM model, and used the cosmological parameters from the WMAP7 data [4]. The background history for $n > 100$ is almost identical to the Λ CDM model. As seen from the section IV, for $n < 100$ the ISW-LSS cross-correlation is negative, which is clearly incompatible with observational data, and the different background evolution does not change the sign of the correlation function and hence is not important. For each parameter, we assume that the galaxy bias is determined by the amplitude of the power spectrum of the matter distribution, $b^{(i)} = b^{(\Lambda\text{CDM})} D_1(z_*^{(i)}) / D_1^{(\Lambda\text{CDM})}(z_*^{(i)})$, where $b^{(\Lambda\text{CDM})}$ is the bias used in the previous section, $D_1^{(\Lambda\text{CDM})}$ is the growth factor of the Λ CDM model, and $z_*^{(i)}$ is the mean redshift of the i -th catalog. Our result implies that the deviation of the effective gravitational coupling from Newton's constant must be very small, as expected in [77]. Since $g_1 \rightarrow 0$ or $g_2 \rightarrow \infty$ corresponds to the Λ CDM model for $a < 1$ the constraint on g_2 can not be determined as long as the Λ CDM model is favored by observations.

Next, we give a forecast for the accuracy of constraining g_1 and g_2 from future galaxy surveys. In the Fisher matrix analysis [78], we consider the following redshift

distribution of the galaxy sample per unit solid angle,

$$\frac{dN}{dz} = \frac{N_g \beta}{z_0^{\alpha+1} \Gamma((\alpha+1)/\beta)} z^\alpha \exp \left[- \left(\frac{z}{z_0} \right)^\beta \right], \quad (17)$$

where α, β, z_0 are the parameters, and $N_g = \int dN/dz$. The mean redshift is determined by

$$z_m = \frac{1}{N_g} \int dz z \frac{dN}{dz} = \frac{z_0 \Gamma((\alpha+2)/\beta)}{\Gamma((\alpha+1)/\beta)}. \quad (18)$$

We used $\alpha = 0.5, \beta = 3, N_g = 35 \text{ arcmin}^{-2}$ and $z_m = 0.9$. We divide the galaxy sample into four redshift bins, $0.05 < z < 0.6z_m, 0.6z_m < z < z_m, z_m < z < 1.4z_m$, and $1.4z_m < z < 2.5$ [79], where the redshift distributions of i -th bin ($z_{i-1} \leq z \leq z_i$) are given by [80]

$$W_i(z) = \frac{A_i}{2} \frac{dN}{dz} \left[\text{erfc} \left(\frac{z_{i-1} - z}{\sqrt{2}\sigma(z)} \right) - \text{erfc} \left(\frac{z_i - z}{\sqrt{2}\sigma(z)} \right) \right], \quad (19)$$

where erfc is the complementary error function, A_i is determined by the normalization constant, and we adopted $\sigma(z) = 0.03(1+z)$. The Fisher matrix is given by [81–83]

$$F^{ij} = f_{\text{sky}} \sum_l (2l+1) \frac{\partial C_l^{\text{ISW-G}}}{\partial \Theta_i} \text{cov}^{-1}(l) \frac{\partial C_l^{\text{ISW-G}}}{\partial \Theta_j}, \quad (20)$$

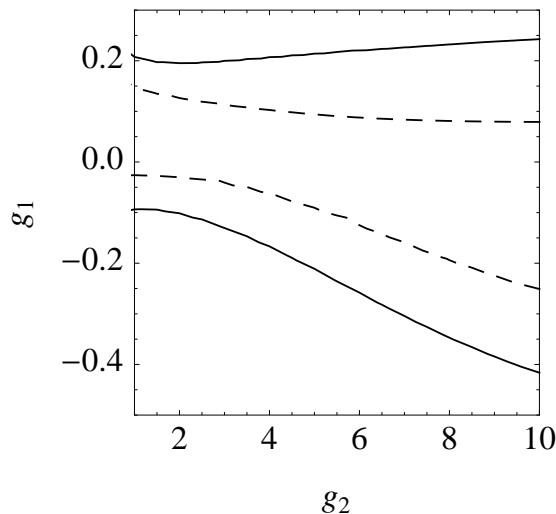


FIG. 2: Contour of $\Delta\chi^2$ on the $g_1 - g_2$ plane. The dashed curve and solid curve are the 1σ and 2σ confidence contour-levels, respectively.

where f_{sky} is the fraction of sky common to both the CMB and the galaxy survey maps, $C_l^{\text{ISW-G}}$ is the two-point angular cross-correlation defined by Eq. (12), Θ_i is the model parameter g_1 and g_2 , and

$$\text{cov}(l) = (C_l^{\text{ISW-G}})^2 + (C_l^{\text{ISW}} + N_l^{\text{CMB}})(C_l^{\text{G}} + N_l^{\text{G}}). \quad (21)$$

Figure 3 shows the 1-sigma (dashed curve) and 2-sigma (solid curve) confidence contours in the $g_1 - g_2$ plane, assuming future survey such as the HSC-like weak lensing survey ($\mathcal{A} = 1500 \text{ deg}^2$) and the LSST-like survey ($\mathcal{A} = 20000 \text{ deg}^2$). The target model is the parametrized model given by Eq. (16) with $g_1 = 0.1$ and $g_2 = 3$. We used the WMAP cosmological parameters for $\Omega_0 h^2$, $\Omega_b h^2$ and $\Delta_{\mathcal{R}}$ and assumed that the bias and the initial amplitude of the fluctuation is determined by individual observations such as CMB power spectra and matter power spectra. Then we consider only 2 parameters g_1 and g_2 in the Fisher matrix analysis. As one can see from Fig. 3, the tomography, by dividing the galaxy sample into several redshift bins, can significantly improve constraints on the parameter g_2 . Therefore, the ISW-LSS cross-correlation with tomography can dramatically improve the determination of the evolution of the effective gravitational coupling as well as its amplitude.

VI. CONCLUSION

In this paper, we have obtained observational constraints on the kinetic gravity braiding model from the cross-correlation function between the ISW effect and the large scale structure. We have found that the cross-correlation function of the kinetic gravity braiding model with small n is negative, and therefore such a model is

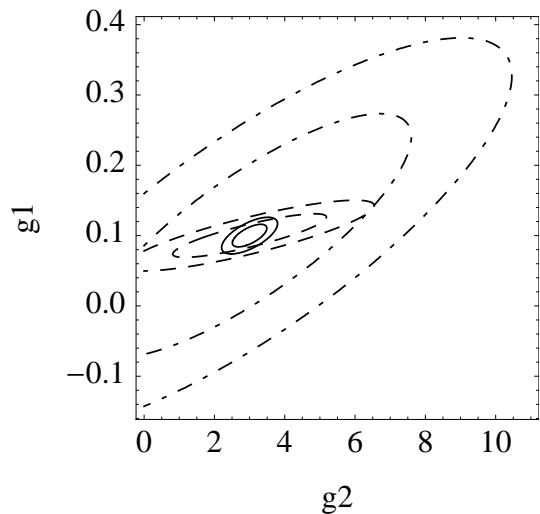


FIG. 3: The 1-sigma and 2-sigma contours in the $g_1 - g_2$ plane for the future survey. We assumed $\mathcal{A} = 1500 \text{ deg}^2 + 4 \text{ bins}$ (dot-dashed curve), $\mathcal{A} = 20000 \text{ deg}^2$ (dashed curve), $\mathcal{A} = 20000 \text{ deg}^2 + 4 \text{ bins}$ (solid curve). The target parameter is $g_1 = 0.1$ and $g_2 = 3$.

not favored by observations. Constraints from ISW-LSS cross-correlation is stronger than those obtained from SNIa and the CMB shift parameter [42]. Thus, the covariant galileon model, $n = 1$, is ruled out by the cross-correlation between the ISW effect and the large scale structure.

In deriving the constraints, we have clarified that the evolution of the effective gravitational coupling is crucial for the behavior of the ISW effect. Motivated by this fact, we also considered the model with a phenomenological parametrization of G_{eff} that can reproduce the effective gravitational coupling of the covariant galileon model. We have confirmed that the deviation from the cosmological constant must be very small: the 1-sigma (2-sigma) error in determining g_1 is $\Delta g_1 \sim 0.15$ (0.3) when $g_2 \sim 2$. We have performed the Fisher matrix analysis, assuming a HSC-like survey and a LSST-like survey, and found that the ISW-LSS cross-correlation with the sample divided into multiple redshift bins can improve significantly the constraint on g_2 . This tells us that the ISW-LSS cross-correlation obtained from the future survey would be a powerful probe for long distance modification of general relativity.

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